THE UNIVERSITY OF TEXAS AT AUSTIN

Semi-Annual Status Report

NASA Grant NSG 44-012-219

(Lunar Motion Analysis)

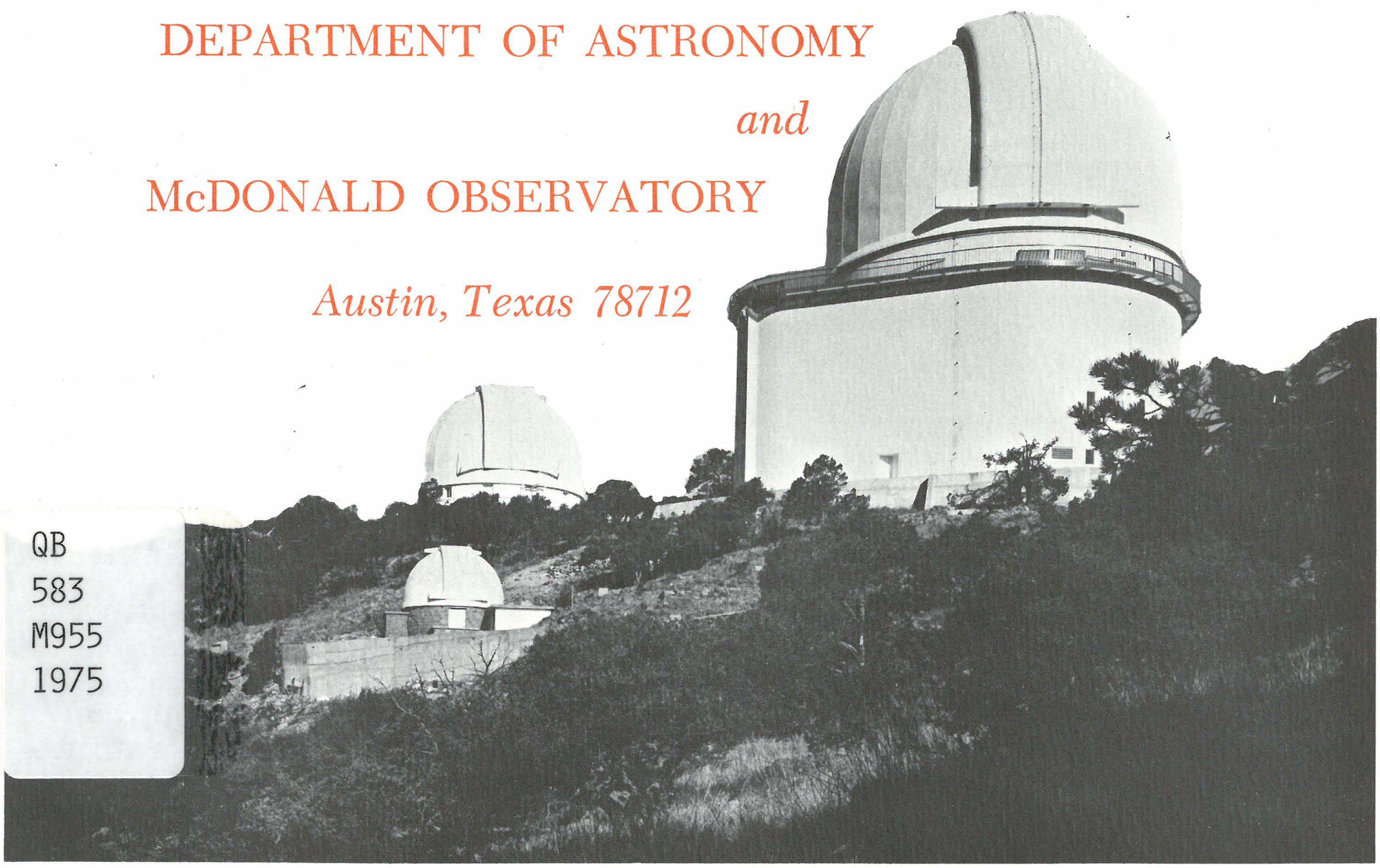
for the period 1974 July 1 - 1974 December 31

DEPARTMENT OF ASTRONOMY

and

McDONALD OBSERVATORY

Austin, Texas 78712



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University of Texas at Austin
Department of Astronomy
Austin, Texas 78712

1975 January

J. Derral Mulholland
Principal Investigator

Abstract

This report covers activity under the subject grant during the second half of calendar year 1974. During this period, in addition to routine data identification and management activities relating to the McDonald Observatory lunar laser data, primary efforts were directed towards 1) improvements in the integration program, aimed at producing the zero-order comparison ephemeris for the "three-dimensional" analysis, and 2) an error modelling study, to estimate the accuracy with which a mobile lunar ranging facility can be located. Other subjects that received attention during this six months include further minor improvements to the analysis model, further progress toward the occultation analysis, a first look at Earth tides, and participation in discussions on the adoption of new astronomical constants and both astronomical and geodynamic coordinate systems.

I. Data Management

The processing of raw data tapes from McDonald Observatory continued throughout the report period. The results were as follows:

Tape ID	Lunation	Photons	Observations	%
MCD67	1974L5	3762	269	7.2
MCD68	1974L6	2887	295	10.2
MCD69	1974L7	3252	335	10.3
MCD70	1974L8	2406	361	15.0
MCD71	1974L9	2037	293	14.4
MCD72	1974L10	2247	275	12.2

A detailed examination of the filtering results for tapes MCD70 and MCD71 showed evidence of photon scatter that was inconsistent with the recorded pulse width and electronic uncertainty. This information was passed back to Dr. Silverberg, and on the basis of our findings he was able to discover a previously unidentified calibration problem that apparently began in 1974 August. Apparently, the correct information is recoverable, but the distribution of observations from tape MCD70 onwards has been postponed until such time as Silverberg's analysis of the problem is complete.

Printed informational copies of residuals with respect to the LURE1 model for reduced normal points for 1974 May - July were sent to all LURE Team members. As per standing request, punch card copies of the residuals were supplied to Team members P. Bender and D. G. Currie, while normal points were sent to D. H. Eckhardt and J. G. Williams. A magnetic tape containing the filtered observations for 1972 July - December and the raw photons for 1973 January - June was deposited in the National Space Science Data Center. The 1972 normal points were submitted for publication in the Astronomical Journal.

Due to the discovery of a few apparently anomalous points, we have undertaken a study of alternative techniques for fitting normal points in the case of peculiar photon distributions. No results are yet available.

II. Ephemeris generation

The previous semi-annual report described the inferential resolution of the published disparity between two computer programs for numerical integration of the solar system orbits. With that problem defused, work resumed on improving the physical model and the numerical integrity of our program, as well as eliminating some inefficiencies, preparatory to our combined fitting of range and occultation data.

Many of the changes to be made result from the fact that the program was originally written for a machine with 54-bit double-precision mantissa, while the UT CDC6600 has 96-bit DP mantissa. A number of vestiges of the smaller precision were not removed in the original program conversion, which was manifested in an exaggerated closure error after a cycle of forward and backward integration to the original starting point. Such closure errors are functions of the angular speed of the object, being most serious for the Moon. The unmodified program returned 15 figures for the Moon after ±400 days, compared with 18 for Earth. The Adams-Cowell coefficients in the finite difference integration algorithm were extended from 16 decimal digits to 28, the effects of figure for both Earth and Moon were converted entirely to double precision, and the input/output formats of starting conditions were extended to 28 figures. After these modifications, the recoverability for Moon and Earth after $\pm 400^d$ was 15 and 20 figures, respectively. That is, the main barrier to realizing our maximum numerical integrity had not been touched. A series of stepsize tests gave evidence that the problem lay in the integration starting procedure, which uses a Taylor series expansion of Keplerian motion (the so-called f and g series). The present hypothesis is that the coded expansion is adequate for other machines, but not ours; it must be extended. This has not yet been accomplished, but is expected soon.

This discovery implied that the defect could be overcome by reducing stepsize (but at higher cost), which was borne out in the tests. Acting upon this result, a new ephemeris (designated UTIE11) was produced for the interval JD 2434800.5-2442800.5 (1954-1976), to be used as a zero-order ephemeris in the "three-dimensional" (i.e. combined range and occultation) analysis. The method of choosing starting conditions at the 1954 epoch was intended to produce an ephemeris that would be observationally indistiguishable from UTIE10 over the interval for which the latter exists (1969-1975), and this goal was satisfied. An hourly ephemeris of lunar apparent places has been computed for the interval 1954-1969 and transmitted to USNO, where the occultation residuals will be computed. The second interval (1969-76) will follow soon.

III. Mobile Station Sensitivity Study

The use of lunar ranging for geotectonics depends on the accuracy with which a temporary station can be located from its own measures. This, in turn, obviously depends on the uncertainty of those measures, the uncertainty of the physical model, the observing geometry, and the weather. In support of the UT Galveston Institute of Earth and Planetary Sciences, where a study of candidate sites is being conducted, we are engaged in estimating this capability on a global basis. Consonant with current design concepts, the measures are assumed to an uncertainty of 3 cm. The largest of the statistical model errors is assumed to be the Earth rotation parameters (universal time and polar motion), which are based on the observations from the fixed stations. At the present stage of the study, each of the three units at McDonald, Haleakala, and Australia is assumed to have 3 cm capability. The accuracy of polar location is then a function of how many of the three stations are observing during the period.

This latter point is important from the standpoint of geographic location of the mobile station, since a station is insensitive to the component of polar motion normal to its meridian.

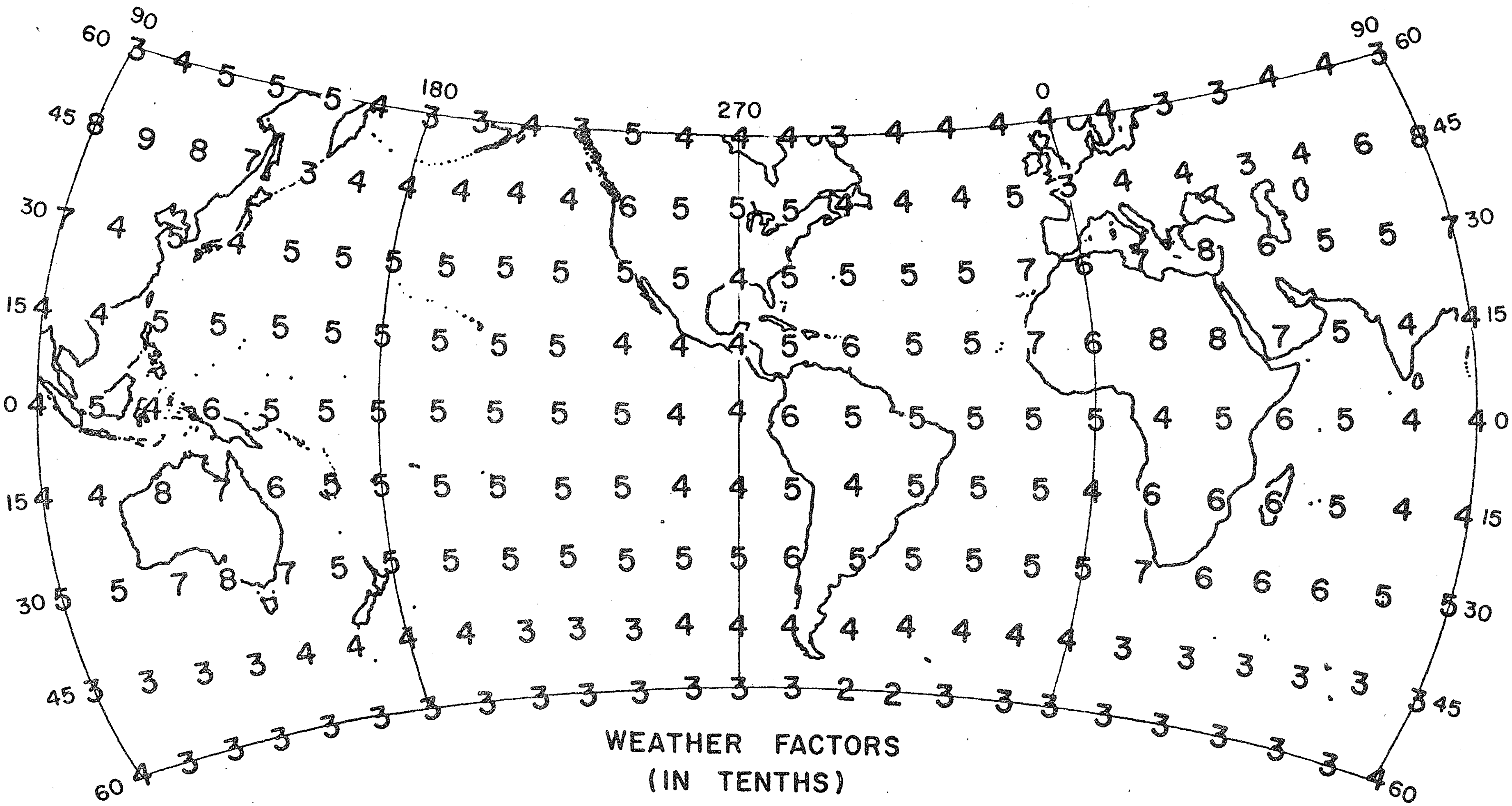
In the calculations, it is assumed that a mobile site will be occupied and capable of ranging for 24 consecutive days and that the observations are scheduled as is currently done at McDonald, i.e. three one-hour periods, at meridian transit and at ±3 hours. A random number generator determines just where in the one-hour interval the observation is located. If the zenith distance is $>70°$, the observation is omitted. Thus, the number and distribution of assumed observations is conservative.

Weather will further reduce the number of observations. Each observation site is assigned a weather factor (program input). A random number generator is combined with a day-to-day correlation scheme, based on the weather factor, to "predict" the weather for a given observation time. To aid in establishing reasonable weather factors, a compilation of worldwide cloud cover was constructed, both on seasonal and annual bases. The annual means produced the data shown in figure 1 (0 = total cloud cover, 10 = totally clear). Using these weather factors and 3 cm pole components from each of the three fixed stations, one obtains the uncertainties for a mobile station as shown in figures 2-4, ΔH being the differential longitude. It must be noted that these represent only the statistical contribution to the total uncertainty, which must be combined with any systematic effects that might exist in the system.

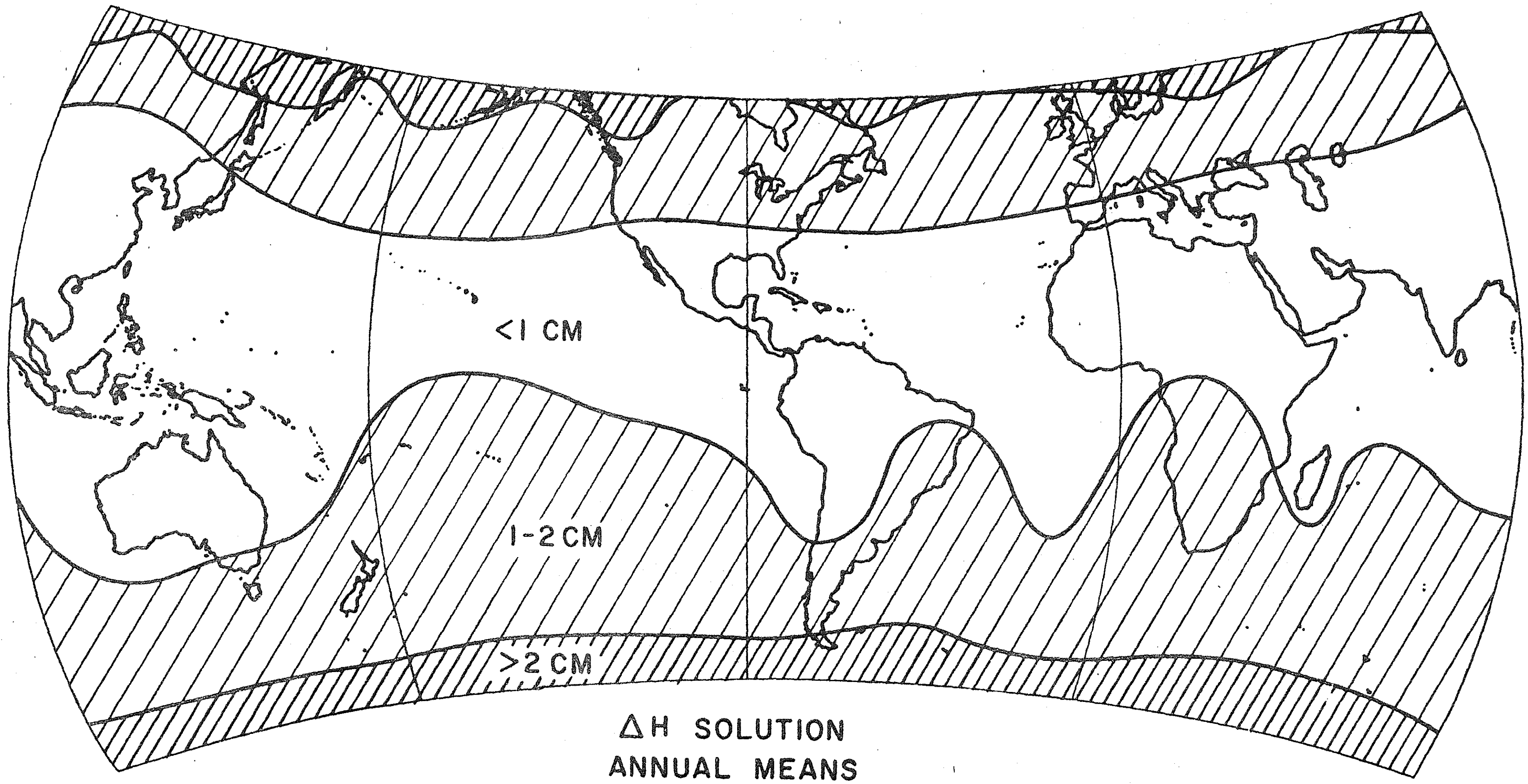
The seasonal maps indicate, as one would expect, considerable variation for some areas. Also, one knows that the spatial variation is often so great that the 15° square area values are frequently much worse than one can find by judicious choice of the exact site. Consequently, we are in the process of producing such error maps for constant weather factors. Maps in topographic coordinates are being produced for the UT Galveston study. A paper describing this work in detail is now being prepared.

IV. Model Improvement and Analysis

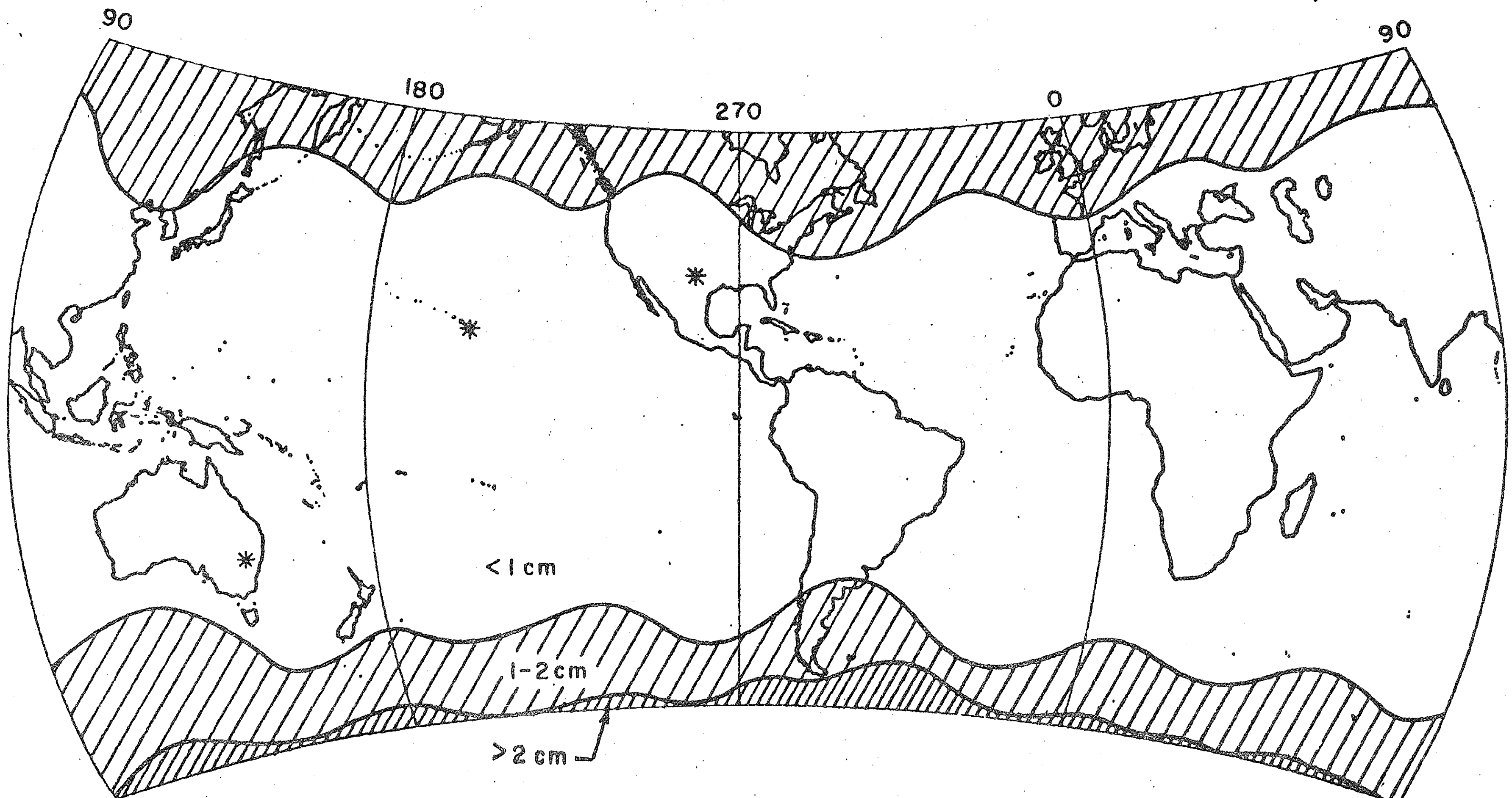
Software has been completed for the inclusion of a theoretical Earth tide model in the calculated ranges. The present model ignores all effects other than the direct tide based on the zenith distance of



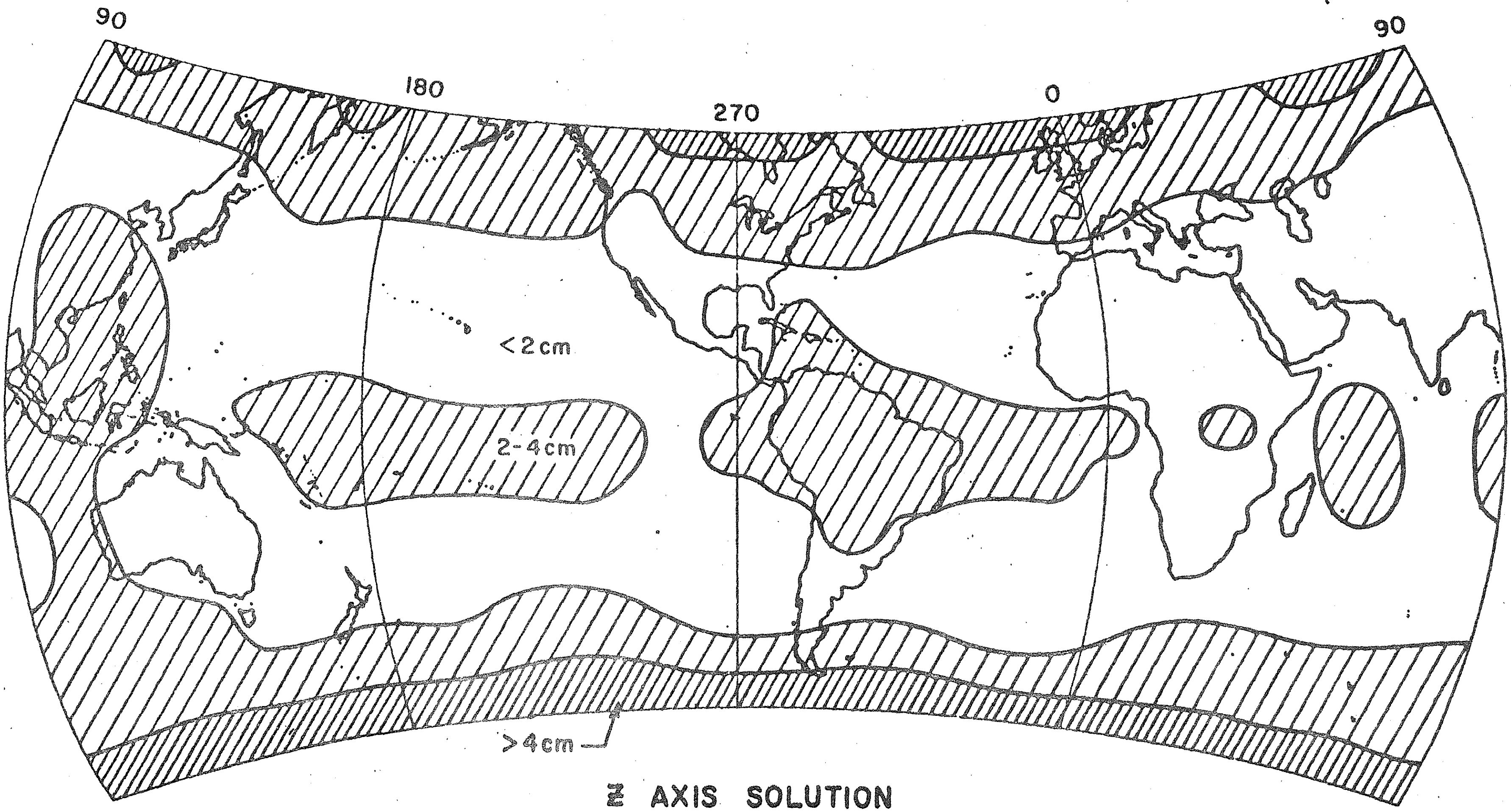
WEATHER FACTORS
(IN TENTHS)
ANNUAL



ΔH SOLUTION
ANNUAL MEANS



AXIAL DISTANCE SOLUTION
ANNUAL MEAN



Z AXIS SOLUTION
ANNUAL MEAN

the perturbing body. Since geometric information is already available in the program, it was decided to avoid the usual expansions as harmonic functions of the lunar and solar elements, but rather to make a direct evaluation of the derivatives of the lunar and solar potential in the form

$$W_2 = G(3 \cos z - 1)$$

The zenith distance is z, while G is a function of the Earth's Love numbers, which are input parameters. We do not know how well this model predicts for McDonald, but Prof. John Kuo (Columbia Univ.) has had a gravimeter in operation at the observatory since January. Once he has a full year's observations, he believes that he can construct an empirical model accurate to 1 cm. It is already evident from preliminary results that ocean loading is important at this level. His model will replace the theoretical one when it becomes available. We are collaborating with Kuo and Silverberg in an effort to obtain a direct measurement of the solid-body tide as a verfication of system accuracy.

Early in the period, a new series of analytic libration solutions (identified as 300) were received from Dr. D. H. Eckhardt. These were used to derive pure power series for the libration angles and their partial derivatives with respect to 2nd and 3rd degree gravitational parameters, as functions of time and the fundamental arguments of the lunar motion. The additional time variability arises due to the variation of the solar eccentricity. This model thus becomes one of several options in our analysis system.

V. Miscellaneous

Mulholland's tenure in residence with the Groupe de Recherches de Geodesie Spatiale (Meudon, France) terminated at the end of August. Much of the last month was devoted to preparation for two working meetings of great importance: the IAU/COSPAR Colloquium on Reference Coordinate Systems for Earth Dynamics (Torun, Poland), where a start was made toward the definition and determination of satisfactory systems for use in ultra-high precision applications, and IAU Working Group on Astronomical Constants and Coordinate Systems (Washington, D.C.), which decided upon a series of sweeping changes to be presented for adoption.

The steering committee appointed by COSPAR Working Group 1 to implement the COSPAR-recommended demonstration of Earth ROtation from Lunar Distances (EROLD), discussed in our previous semi-annual report, consists of the following members: C. O. Alley (ex officio), O. Calame (France), B. Guinot (BIH), Yu. L. Kokurin (USSR), Y. Kozai (Japan), P. Melchior (IUGG), P. Morgan (Australia), and J. D. Mulholland (USA, chairman).

So that the collaborating astronomers and geophysicists could gain more insight into the overall problem of doing tectonic studies by lunar ranging, a two-day seminar was held at Austin, December 18-19, for informal discussions of topics of interest, including plans for the first phase of mobile station operations. These sessions were attended by Eric Silverberg of McDonald Observatory, five members of the Galveston group, nine persons from the Austin campus, John Kuo of Columbia, and

Col. Strickland, our NASA project monitor. It was a fruitful series of discussions, parts of which will appear in print.

VI. Staff, Publications and Travel

During the report period, the project staff consisted of J. D. Mulholland (P.I. 5 man-months), R. I. Abbot (3 mm), D. W. Dunham (1 mm), G. Loumos (2 mm), N. Otto (5 mm) and P. J. Shelus (6 mm). Dunham terminated his connection with the project on August 31, Abbot on December 31. Loumos, who is working on the sensitivity study, joined the project on September 1.

Publications during the report period (abstracts appended) include:

Bender, Currie, Mulholland and Williams, "Preliminary Determination of the Earth's Rotation from Lunar Laser Range Measurements" EOS 56, 1105, 1974 (abstract).

Mulholland, "The Rotation of the Moon" accepted for publication by Acad. Roy. Sciences Belgique.

Mulholland, "Coordinate Systems in Lunar Ranging" accepted for publication in proceedings of IAU Colloquium 26.

Shelus, Mulholland, and Silverberg, "Laser Observations of the Moon: Normal Points for 1972" accepted for publication in Astron. J.

Mulholland and Shelus attended the September LURE Team meeting in Boulder. Mulholland attended the October GEOP meeting on selenodesy and lunar dynamics and made one trip to NASA/JSC. Abbot received partial expenses to participate in the December meeting of the American Astronomical Society.

geoid height problem will be presented at the next meeting of the AGU.

G 11

APPLICATIONS OF NORMAL EQUATION REORDERING AND HELMERT BLOCKING TO THE NEW ADJUSTMENT OF THE NORTH AMERICAN DATUM

Robert H. Hanson (Geodetic R&D Lab., National Ocean Survey, NOAA, Rockville, MD 20852) (Sponsor: Nancy L. Morrison)

The new adjustment of the primary geodetic control network in the United States requires the solution and inversion of normal equations for approximately 200,000 stations. A proposed system for accomplishing this monumental task is presented. Basic components of the system are (1) a program using the Cuthill-McKee algorithm for reordering normal equation unknowns to minimize storage and computing requirements, (2) a triangulation adjustment program featuring a matrix reduction/solution/inversion subroutine based on a Cholesky factorization program developed by Poder and Tscherning of the Danish Geodetic Institute, (3) use of the Helmert-Wolf blocking technique to partition, reduce, solve and invert the system of equations, and (4) a technique for a posteriori error propagation involving functions of any unknowns, including those unknowns located in the same block, in different blocks, or on different levels of blocks.

G 12

CORRECTIONS TO HORIZONTAL OBSERVATIONS IN SEISMIC AREAS AS A FUNCTION OF TIME

J. F. Dracup (National Geodetic Survey, NOS, NOAA, Rockville, Maryland)

Problems involving the national horizontal control network, which result from seismic activity, increase with time and are compounded to some extent where regional subsidence, due to the removal of underground resources, has occurred. Nowhere in the United States is the situation more acute than in California. With the new adjustment of the North American Datum underway, some alternative to a crash program of reobserving the network in affected areas is necessary. Although some reobservations will undoubtedly be required, it seems logical and practical to update the original or latest observations, utilizing available information. To briefly examine the situation - at any instance of time, the displacement at a particular station is constant with respect to distance and direction; and if known, the observations can be corrected, provided there has been no discontinuity since the latest observations were secured. In many areas, sufficient data are available to calculate acceptable vector estimates; although at this point in the development of the concept, some refinements are possibly still to be considered.

G 13

THE RELATION OF GRAVITY CHANGE AND ELEVATION CHANGE IN SEDIMENTARY BASINS

W. Strange
D. Carroll (both at: NOAA-NOS, National Geodetic Survey, Rockville, Maryland

In 1969, gravity reobservations were obtained at a large network of stations in the central valley of California which had been observed originally in 1962. Changes in observed gravity of up to +0.6 mgals were observed due to land subsidence. Correlations of gravity change with elevation change, based on releveling, showed that gravity change could be used to predict elevation change with an rms accuracy of about $\pm$15 cms. This degree of agreement represented about the maximum to be expected considering the accuracy of the gravity data.

Limited reobservations were also carried out in the Houston, Texas area. The value of gravity at IGBN station HOUSTON D has increased by 0.25 $\pm$0.1 mgals between 1966 and late 1973 based on connections between Houston and Austin, Texas. This is in general agreement with subsidence between 1963 and 1973 indicated by releveling.

G 14

NEW GRAVITY TIDE MEASUREMENTS AND AN EXPERIMENT TO LOOK FOR EVIDENCE OF A "PREFERRED UNIVERSAL FRAME"

T. Whorf
J. Berger
R. Haubrich (all at: Institute of Geophysics and Planetary Physics, La Jolla, California)
R. Warburton (University of California San Diego, La Jolla, California)

Earth tide gravity has been recorded for over a year at the Piñon Flat Observatory in Southern California, using two gravimeters, a modified LaCoste-Romberg and the superconducting gravimeter. Tidal signal exceeds background noise by up to 75 db. Data analysis has separated those effects due to solid earth tide, ocean loading and solar radiation. In addition we have searched for changes in gravity at tidal frequencies which are predicted by gravitational theories having a preferred universal reference frame. It has been shown recently, that such theories predict anomalous siderial earth tides as a result of the velocity of the Earth relative to this frame. Our method of analysis allows ocean tidal loading to be modelled in terms of a smoothly varying admittance with solar radiation effects as additional inputs. An examination of the residual spectrum, obtained by subtracting the "best fit" model from the data, shows 1) lines at tidal frequencies which possibly result from nonlinear frictional effects in the ocean, 2) a "cusping" in the background noise near 1 and 2 cpd at levels about 65 db below peak signals, and 3) no evidence of a preferred-frame anomaly greater than 1×10^{-10}g.

G 15

GEOLOGICAL INTERPRETATION OF GRAVITY AND MAGNETIC SURVEYS OF KEENE DOME IN NEW ENGLAND

F. I. Ahmad (Seiscom Delta, Inc., P.O. Box 36789, Houston, Texas)

Gravity and magnetic study of the central part of Bronson Hill anticlinorium indicates that geophysical data correlates well with the geologic map except in the southeastern part of the Keene-Brattleboro area. A linear gravity high of 8 milligals overlies Keene dome gneiss of 2.70 gm/cm^3 density and 0.38×10^{-3} cgs magnetic susceptibility. Gravity modeling suggests that the gravity high is an expression of a shallow subsurface linear amphibolite body with 2.97 gm/cm^3 density and 0.12×10^{-3} cgs magnetic susceptibility. The top of 1500 meters wide body is estimated to be 180 meters below ground surface with bottom at 2400 meters depth. A synthesis of geophysical and geological data suggests that the amphibolite body is a dragged, detached and sucked up portion of a thin layer of mafic volcanics in dome gneisses and was formed with doming processes of the Keene dome.

G 16

PROJECT ARIES: AN ACCURACY DEMONSTRATION OF RADIO INTERFEROMETRIC SURVEYING ON A 307-METER BASELINE

K. M. Ong
P. F. MacDoran
J. B. Thomas
H. F. Fliegel
L. J. Skjerve
D. J. Spitzmesser
P. B. Batelaan
S. R. Paine
M. G. Newsted (All at: Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif.)

A precision geodetic measurement system (ARIES for Astronomical Radio Interferometric Earth Surveying) based on the technique of very long baseline interferometry (VLBI) has been designed and implemented through the use of a 9-m transportable antenna together with the 64-m Goldstone antenna of the Deep Space Network. A series of experiments aimed at demonstrating the inherent accuracy of the transportable interferometer concept independent of transmission media, radio source position and earth rotation parameters effects were performed on a 307-m baseline during the period from December 1973 to June 1974. The line-of-sight separation between the antennas were surveyed in three dimensions by conventional means. Results of these experiments showed that the interferometric technique is capable of few centimeter baseline measurement precision in all three components which also agree with the ground survey to that accuracy. The ARIES transportable antenna has now entered its next phase of demonstrations over a 180 km baseline (Goldstone to JPL, Pasadena) and initiated a tectonic motions monitoring program within the southwestern United States.

SATELLITE GEODESY (G)

Marina-Sea Cliff Room (JT)

Friday 0900h

G 17 INVITED PAPER/30 MINS.

CRITICAL REVIEW OF THE CURRENT STATUS OF THE GEOCENTRIC GRAVITATIONAL CONSTANT

Dr. Pasquale B. Esposito (Member of Technical Staff Tracking & Orbit Determination, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91103)

G 18

DETERMINATION OF THE MASSES OF THE EARTH, MOON AND SUN AND THE SIZE OF THE EARTH FROM MARINER 9 RANGE AND RANGE-RATE OBSERVATIONS

C.F. Martin (Wolf Research and Development Corporation, Riverdale, Maryland)
S.M. Klosko (Wolf Research and Development Corporation, Riverdale, Maryland)
J.W. Ryan (Goddard Space Flight Center, Greenbelt, Maryland)

S-Band observations of tracking Mariner 9 by the JPL Deep Space Network (DSN) have been used to estimate the values of GM_E of 398600.9, GM_S of 1.327129×10^{11}, and GM_M of 4902.802 Km^3/sec^2. DSN station coordinates were also determined.

The simultaneous solution contains four data spans generally separated at maneuvers. Data processing included correction for ionospheric refraction based on a global model. Recovered longitudes are consistent to within 1m of those of JPL (Mottinger, 1973), with the exception of Joburg which differs by ~3m. Recovered spin axis distances are 0.5—3.5m larger than those of JPL and are in better agreement with those of Marsh et al (1973) and Lerch et al (1972) than are those of JPL. The recovered spin axis distances imply a value of $a_e = 6378144 \pm 4$m.

Error analysis of the recovered mass values of GM_E, GM_S, and GM_M give estimated errors of less than 0.2 ppm, 1. ppm and 2. ppm respectively. The accuracy of the recovered values for spin axis distances and relative longitudes are assessed at less than 1.5m. There is little apparent longitude rotation between our recovery and that of Mottinger 1973.

G 19

PRELIMINARY DETERMINATION OF THE EARTH'S ROTATION FROM LUNAR LASER RANGE MEASUREMENTS

P.L. Bender (Nat Bur of Standards and Univ of Colo, Boulder, Colo)
D.G. Currie (Univ of Md, College Pk, Md)
J.D. Mulholland (Univ of Texas, Austin, Texas)
J.G. Williams (Jet Propulsion Lab, Pasadena, Calif)

Improvements have been made recently in the numerical integration of the lunar motion and in the calculation of the librations. Fits with ±40 cm rms residuals now can be obtained for over 4 yrs. of data from the McDonald Obs. (104°W, 30°N). BIH values for UT1 and polar motion were used, plus a linear drift and a small annual term in UT0. Preliminary UT0 corrections were calculated from the residuals for 153 days on which range measurements are available for times differing by at least 3 hr. The best, 1st quartile, and median accuracies are 0.22, 0.37, and 0.48 millisec, including allowance for the uncertainty in the 104°W component of the pole position. Small additional corrections are needed, but the general agreement with the interpolated BIH values is good. For the 55 pairs of successive days on which UT0 corrections were obtained, the mean absolute difference was 0.5 ms. A new value of GM for the earth-moon system also is being obtained, as well as improved McDonald Observatory coordinates.

G 20

SOME OBSERVATIONS OF OCEAN BACKSCATTER USING SKYLAB S-193 RADAR ALTIMETER AGC DATA

C. L. Parsons (National Aeronautics and Space Administration, Wallops Island, Virginia 23337)

During the SKYLAB missions of 1973 and 1974, the S-193 satellite altimeter, a nadir pointed radar system operating at a frequency of 13.9 GHz., was

MÉCANIQUE CÉLESTE

The Rotation of the Moon (*)

J. DERRAL MULHOLLAND (**)
Groupe de Recherches de Géodésie Spatiale
Meudon, France

I. INTRODUCTION

The synchronous rotation of the Moon was one of the earliest telescopic discoveries, and this now-common feature was for long thought to be unique in the solar system. Observing that the synchronism was accompanied by a resonant axis motion, Cassini determined the geometric laws that describe the gross rotation relative to the precessing lunar orbit in terms of the mean orientation elements of the orbit. When combined with the geometry of the true orbit motion, the rotation implies an apparent rocking of up to about 11°, which is readily observable even with rather crude instruments. This apparent motion is customarily designated the " optical libration, " a term that seems to imply that there is no need to analyze it. It is not, in fact, the entire rotational motion. By custom, the residual part, which can exceed 100″ is called the " physical libration ", a term that implies a mechanism for analysis. This is in fact true; differential equations can be written for the departures from the Cassini motion, forced by the gravitational action of the Earth on the non-spherical figure of the Moon. This has been the path for all discussions of the lunar rotation.

The separation into optical and physical librations is quite artificial, however useful it may be. In this review, I shall try to give a comprehensible demonstration that the Cassini motion is an approximation to a dynamically-consistent system, without being an exact solution to any simplification of the problem. Further, the traditional approaches to the derivation of the physical librations will be given, without some of the mystery of the available discussions. Recent studies, motivated by the existence of new high-precision observations and exposing some serious omissions in the available theories, will be reviewed. Finally, the present status of the problem will be discussed, along with some suggestions for the future.

(*) Presented at the *Journées Luxembourgeoises de Géodynamique*, 14-15 January, 1974.

(**) On partial leave from University of Texas at Austin, U.S.A.

Présenté par M. Ch. MANNEBACK.

II. NOTATION

A, B, C	Principal moments of inertia of Moon
a, ***b***, ***n***	Unit vectors for lunar orbit coordinate system
a	orbital mean distance
b	selenographic latitude
C_{nm}, S_{nm}	Gravitational harmonic coefficients
E	Earth mass
e	orbit eccentricity
F	argument of latitude $= L - \Omega$
f	true anomaly
G	gravitational constant
g	mean anomaly
I	inclination of lunar equator on ecliptic
i	orbit inclination on ecliptic
i, ***j***, ***k***	Unit vectors for principal axis coordinate system
K	lunar rotational angular momentum vector, $K = \lvert \mathbf{K} \rvert$
k_2	tidal Love number for Earth
L	Orbital mean longitude
l	selenographic longitude
M	mass of Moon
n_c	sidereal mean motion
n	anomalistic mean motion
P	period
P_n	Legendre polynomial of degree n
P_n^m	Associated Legendre polynomial of degree n and order m
p_i	Direction cosines of ecliptic pole ($i = 1, 2, 3$)
Q	Dissipation parameter for Earth

COORDINATE SYSTEMS IN LUNAR RANGING

J. DERRAL MULHOLLAND
Groupe de Recherches de Géodésie Spatiale, Meudon, and
The University of Texas at Austin

Prepared for presentation at IAU Colloquium 26, Reference Coordinate Systems for Earth Dynamics, Torun, Poland, 1974 August 26-31

Introduction

The excitement associated with the concept of Earth dynamics, the realization that our planet is not rigid but exhibits various types of measurable distortions, has motivated the development of new techniques for determining these intrinsic motions with a precision sufficient to improve our knowledge of the causative processes. One can imagine three general categories of such techniques: the measurement of some physical property (such as gravity) that is related to location; the direct measurement of relative movement between points in or on the Earth's crust (as with strain meters); and the indirect monitoring of either the "absolute" or differential coordinates of surface points by observations of extraterrestrial objects. This latter seems to be the only category that permits one to study the global state of the Earth, and it alone is heavily dependent on the definitions of coordinate systems. One such technique that is capable of yielding site coordinates with accuracies of a few centimeters is lunar laser ranging (1,2), in which one measures the time delay (or aberration) of a photon as it makes the traverse from a transmitting telescope on the Earth's surface to a reflective device on the lunar surface and then back to a receiving telescope on Earth. In the usual; and simplest, realization of this process, transmission and reception are accomplished by the same telescope.

Laser observations of the moon: Normal points for 1972

Peter J. Shelus and J. Derral Mulholland

McDonald Observatory and Department of Astronomy, University of Texas at Austin, Austin, Texas 78712

Eric C. Silverberg

McDonald Observatory, Fort Davis, Texas 79734

(Received 20 November 1974)

The lunar laser observations taken at the McDonald Observatory during 1972 are presented in the form of compressed normal points, using the technique of an earlier paper. Refinements in the knowledge of the lunar motion have permitted corresponding increases in the ability to discriminate observations contaminated by equipment malfunctions; a list of amendments is given for the 1969–1971 data. The geometry of the telescope must be taken into account in the application of these data.

INTRODUCTION

THE 2.7-m (107-in.) telescope of the McDonald Observatory is engaged in a regular program of laser-range observations to reflector arrays on the lunar surface. These data provide information on several aspects of lunar physics, geophysics and dynamical theory. The scientific rationale underlying this project has been discussed elsewhere (Bender, Currie *et al.* 1973), as have the technical details of the observing process (Silverberg 1974). This is the second in a series of papers on the observations themselves. The first (Abbot, Shelus *et al.* 1973, referred to later as Paper I) gave a detailed description of the process used to filter the observations from noise. While the raw data and the filtered observations are placed in the public domain on a regular schedule, few users will wish to work at the individual photon level. Consequently, Paper I also described the technique that we have adopted to compress the data into normal points, each one representing a few minutes' observations. These normal points were tabulated for the years 1969–1971. The observations for 1972 are now available, and the corresponding normal points are presented here. The processes described in Paper I remain valid for these data.

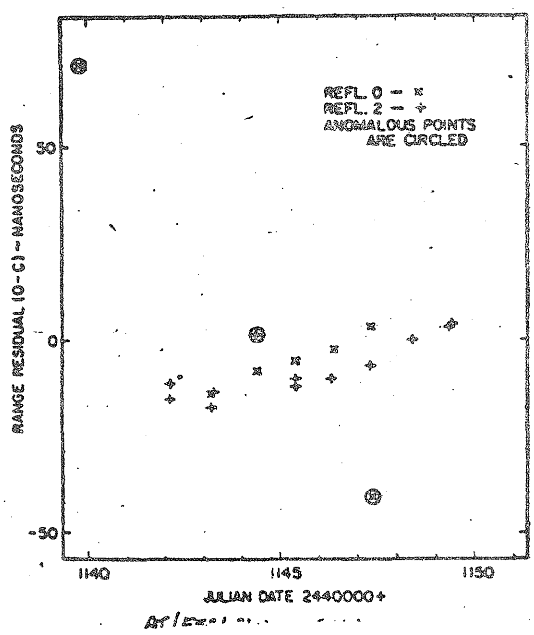


FIG. 1. An example of the identification of real observations with faulty timings, due to equipment malfunction.

I. DATA AMENDMENTS 1969–1971

While it is true that the data identification process has not been changed in principle, it is also true that the sensitivity of this process to certain types of spurious timings has increased quite notably since Paper I. This is because the physical model of the lunar orbit and the lunar rotation has been improved drastically by the discussion of the laser data (papers in preparation), refining the degree to which day-to-day consistency can be imposed on the photon detection as a criterion for rejection. This has no influence on the rejection of random-noise photons. As noted in Paper I, however, certain equipment malfunctions can cause erroneous timing of true observational events. Several such instances have been found, particularly in the early data, when the most common mode involved extra pulses from the basic 20-MHz clock oscillator. Thus, an occasional observation was mistimed by some integer

TABLE I. Points to be deleted from the list given in Table II of Paper I. T^* is the equivalent Julian date of observation.

T^* (UTC) 2440000+
467.9813749999
842.5868425917
849.0979814816
868.6441875204
903.6340138939
989.7289236148
989.7405605196
1044.5537361129
1060.1382118086
1103.5105337286
1139.7300555603
1145.0833333376
1148.0523263927
1227.7445836823